Global Soil Moisture Retrievals from the WindSat Spaceborne Radiometer

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Abstract

Originally designed for detecting ocean surface vector winds, WindSat is the first spaceborne polarimetric microwave radiometer built on the heritage of other satellite microwave radiometers such as SMMR, SSM/I and AMSR-E, thus has a wide range of applications in ocean and land remote sensing. To this end, a physically-based land algorithm was developed to retrieve global soil moisture and vegetation water content from WindSat data. The retrievals are validated using in-situ data from U.S. and Mongolia. The U.S. data sets were acquired during series of Soil Moisture Field Experiments (SMEX) at different sites, including Oklahoma in 2003, Arizona in 2004 and Iowa in 2005. Despite of their relatively short temporal coverage in the summer, these three experiment sites provided diverse land/vegetation covers (rangeland, winter wheat, sparse scrubland, agricultural domain with corn and soybean) and extreme wet/dry soil conditions. The Mongolia data set was collected by JAXA using a distributed in-situ network. In general, WindSat retrieved global soil moisture and vegetation water content distributions are very consistent with dry/wet patterns of climate regimes. The volumetric soil moisture retrievals agree very well with the in-situ data from all the sites with an uncertainty of about 4% and bias of 0.4% at 50 km Horizontal Cell Size (HCS). The retrieved soil moisture is highly correlated with in-situ data with a correlation coefficient of 0.89. Spatial patterns of the retrieved soil moisture are also consistent with precipitation maps generated with NEXRAD radar data. In addition, good consistency is also obtained between WindSat retrieved Vegetation Water Content and AVHRR derived Green Vegetation Fraction data produced operationally by NOAA/NESDIS.

Algorithm Development

Introduction:

The WindSat was built on the heritage of other satellite microwave radiometers such as AMSR-E, TRMM/TMI, SSM/I and SMMR, and added the polarimetric capability enabling it to resolve the ocean surface wind vector. Its radiometer operates in discrete bands at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. The 10.7, 18.7 and 37.0 GHz channels are fully polarimetric, while the 6.8 and 23.8 GHz channels are dual polarized only (vertical and horizontal). Therefore WindSat has a wide range of land applications beyond ocean remote sensing. To this end, and to provide algorithm risk reduction for NPOESS future Microwave Imager/Sounder (MIS) mission, we developed new land algorithms that retrieve soil moisture and vegetation water content based on WindSat data. The new algorithms were validated using in-situ data acquired during soil moisture field experiments. Despite their relatively short temporal coverage, these experiment sites provided diverse land/vegetation covers and wet/dry soil conditions. In general, WindSat volumetric soil moisture retrieval uncertainty is about 4% with 0.4% bias at 50 km Horizontal Cell Size (HCS). The retrieved soil moisture is highly correlated with in-situ data. Spatial patterns of the retrieved soil moisture are consistent with precipitation maps generated using NEXRAD radar data; and retrieved global soil moisture distributions are consistent with dry/wet patterns of climate regimes. In addition, good agreements are also obtained between WindSat retrieved Vegetation Water Content and AVHRR derived Green Vegetation Fraction data produced by NOAA/NESDIS.

RFI (Radio Frequency Interference) Mitigation:

RFI detection and mitigation are essential for C- and/or X-band passive microwave sensors. Electromagnetic surveys indicate strong and dense networks of C-band RFI in the United States, Japan, and the Middle East, with sparser concentrations in Europe (Li et al., 2006a). The X-band RFI is found mostly in Europe and Japan. When RFI is not an issue, C- and X-band data are very useful in land applications. Currently many land algorithms developed avoid the use of C-band data and heavily focus on the US (e.g. Njoku and Chan, 2006; Jackson et al., 2005; Koike et al., 2000). This does not mean that C-band is of no value, it means that it is difficult to operationally correct for RFI with current sensors.

The MIS (Microwave Imager/Sounder) is a replacement mission for CMIS (Conical-Scanning Microwave Imager/Sounder), which was cancelled by NPOESS due to budget constrains. CMIS had selected the a sub-band technique to provide a hardware solution for RFI mitigation, which works best when a majority of the sub-bands are RFI-free. However this approach is not completely risk free since future RFI could potentially corrupt all the CMIS sub-bands. Sub-band channels are not available on WindSat, and will not likely be available on the MIS mission. Therefore, a data analysis and processing solution with/without sub-band data should be considered as an RFI risk reduction tool for the MIS mission. To this end, a WindSat RFI correction algorithm was developed using a novel multivariate-based spatial-spectrum filter technique that can be used with and without sub-bands (Li et al., 2006b). Figure 1 shows a plot of WindSat RFI corrected C-band Tb along with measured Tb for X- and Ku-band horizontal polarization channels. For C-band, the predicted RFI-free Tbs are plotted only in the RFI-contaminated regions, and the original measurements are plotted in the RFI-free regions.
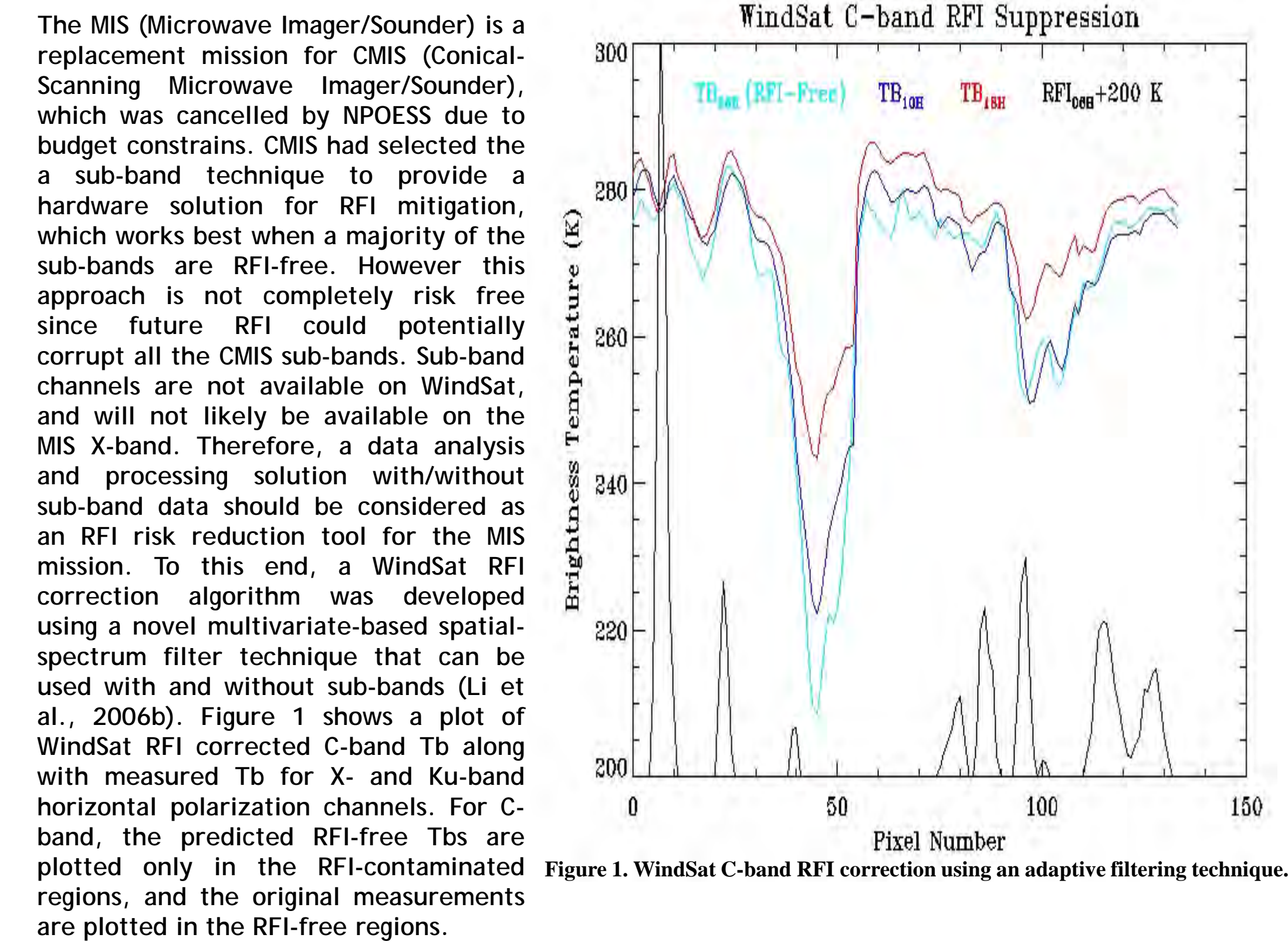

Figure 1. WindSat C-band RFI correction using an adaptive filtering technique.

The RFI correction results can be evaluated using airborne sub-band data if one of the multiple sub-bands is always considered to be RFI-free. Alternatively, we can also test the RFI corrected data against the land algorithm performance to evaluate their benefits. To illustrate the first approach, Figure 2 shows a case study of RFI correction for the Airborne Polarimetric Microwave Imaging Radiometer (APMIR) 6.8 GHz horizontal polarization data over a flight line during SMEX05 on July 2, 2005. Fig. 2(a) is a plot of the RFI corrected 6.8 GHz Tb along with the RFI-free Tb measurements made in the 7.2 and 10.7 GHz channels. Reasonable correlations among the different channels are retained over the entire flight line. Fig. 2(b) plots RFI intensity predicted by the algorithm, showing two unregistered moderate to weak RFI sources. Fig 2(c) is a scatter plot of the 7.2 GHz RFI-free data versus the 6.8 GHz RFI corrected data. There is an apparent constant offset of about 2 K between the 6.8 and 7.2 GHz data. While it is reasonable to have a small offset between them associated with physical phenomena, the 2 K offset is too large to be explained by any model and is most likely associated with calibration bias between channels. Nevertheless, Fig. 2(c) demonstrated a channel correlation of 0.97 between the 6.8 and 7.2 GHz channels, suggesting good recovery of the 6.8 GHz data.
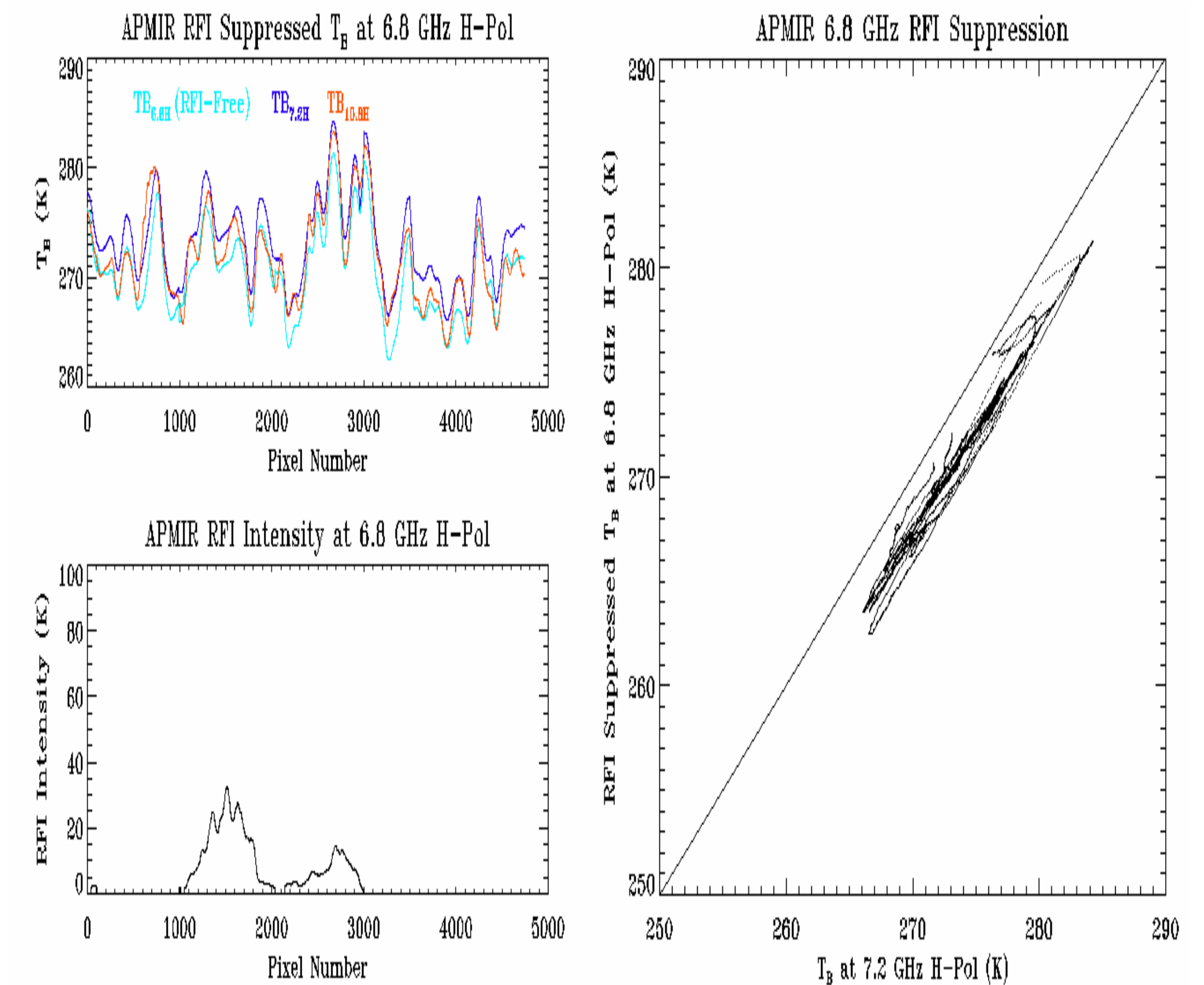
WindSat Soil Moisture Algorithm:

WindSat land algorithm is a physically-based multi-channel maximum-likelihood estimator using 10, 18, and 37 GHz data. The 6 GHz data were excluded for the mitigation of the RFI problems [9]. The solution is found by iteratively minimizing the distance between radiative transfer simulations and measurements in the brightness temperature measurement spaces. In this way, we can provide retrievals that not only are consistent with radiative transfer model but also handle directly the nonlinearity of the vegetation effects and non-uniqueness of the solution.

For a land surface with a layer of vegetation canopy, the land emission can be approximated using the τ–ω model,

$$e_{bp} = T_{bp}/T_s = e_{sp}\exp(-\tau_c) + (1-\omega_p)(1-\exp(-\tau_c))(1+r_{sp}\exp(-\tau_c))$$

The brightness temperature observed by satellite instrument (TBP) is further modified by atmospheric emission and attenuation,

$$T_{Bp} = T_{Bu} + \exp(-\tau_a)(T_{bp} + r_{bp}T_{Bd})$$

For the inverse model, let us define the geophysical state vector x = {mv, wc, Ts}, where mv is soil moisture, wc vegetation water content, and Ts land surface temperature; the corresponding calculated multi-channel brightness temperature and/or their combination, such as polarization ratio, are y ={ysj}, where j is the channel number. The noisy measurement ymj can be written as,

$$y_{mj}(x) = T_{Bsj}(x) + n_j$$

where nj is the measurement noise of Gaussian distribution with zero-mean and variance sigma. Then for a given geophysical state x, the log likelihood function LH(x) for x, given all the measurements, is then

$$LH(x) = \sum_j \log(p(y_{mj}|x)) = -\frac{1}{2}\sum_j \log(2\pi\sigma_j^2) - \sum_j \frac{\{y_{mj}-y_{sj}(x)\}^2}{2\sigma_j^2}$$

In this way, the state variable x can be retrieved using maximum likelihood estimation.

Frequency Dependence
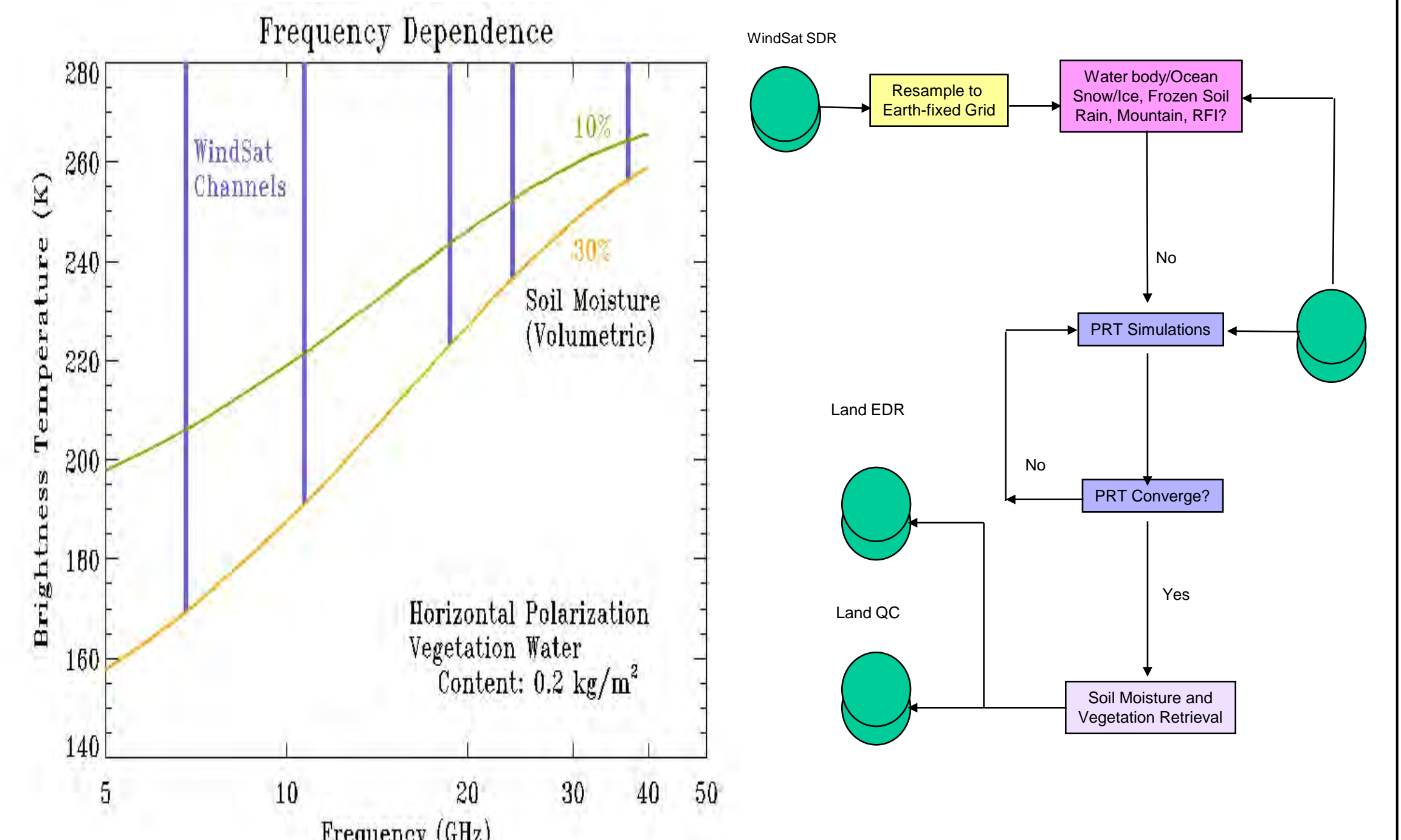
Comparison with precipitation patterns

- **Data Scales:** Comparing soil moisture and precipitation patterns offers a qualitative but effective way to validate soil moisture retrievals at spatial synoptic and mesoscale scales that are much larger than the coverage of in-situ networks
- **Case 1 — Synoptic Scale:** The widespread and significant rain events on 9/11/2003 over great plains created saturate ground following an extreme drought conditions. The WindSat overpass the next day shows clearly a high soil moisture pattern overlapping with the rain pattern.
- **Case 2 — Mesoscale:** The NEXRAD radar reflectivity revealed a localized T-Storm over northeast Iowa on 6/26/2005. The WindSat overpass during the storm shows saturated soil moisture pattern that is consistent with NEXRAD data. The grey area around the center of the storm is classified as precipitation by Windsat algorithm and no retrieval is performed.

Case 1– Synoptic Scale   Case 2 – Mesoscale

NEXRAD 6/26/05   WindSat 6/26/05, 12:26 UTC
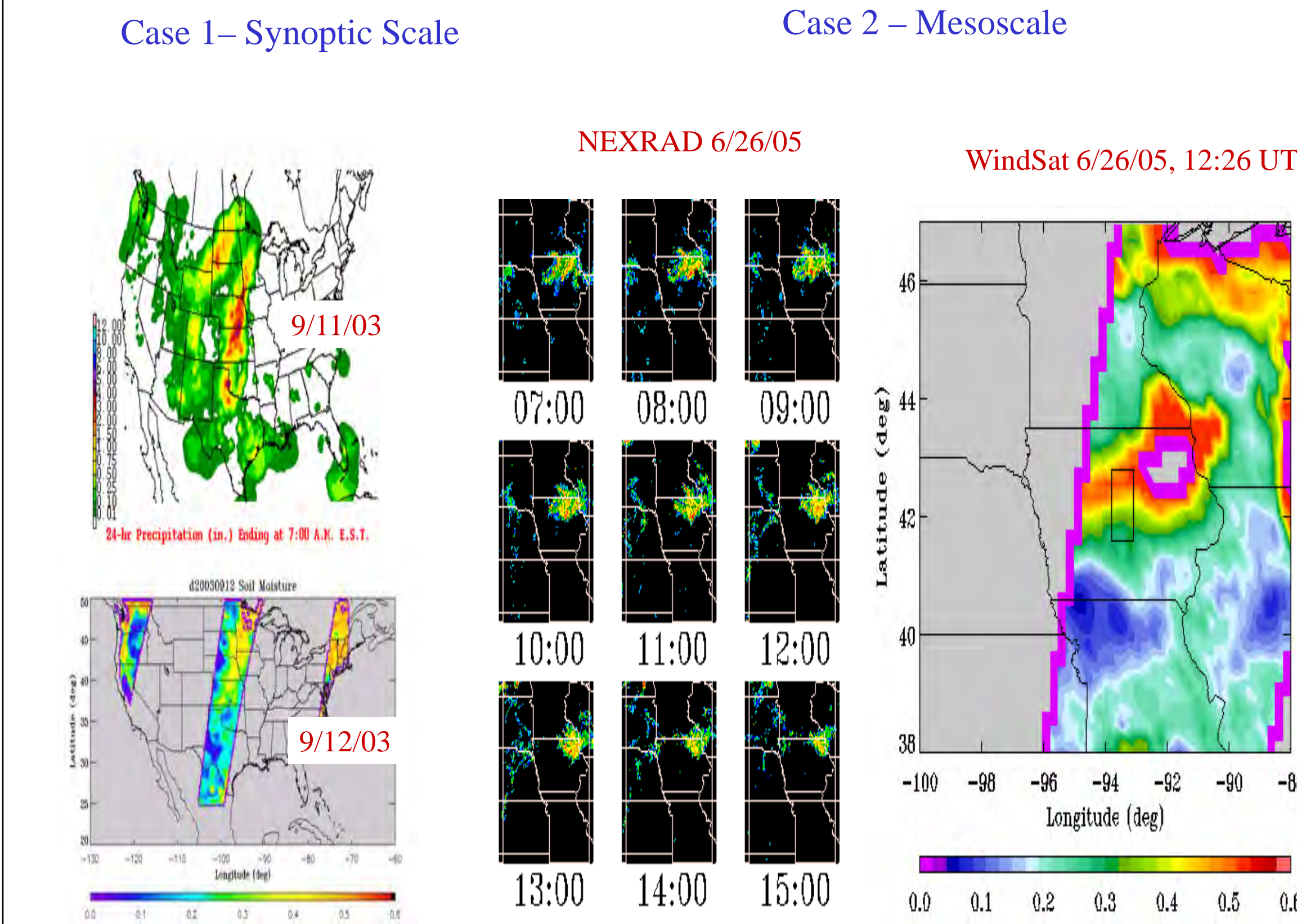
Validation Results

We examine land retrievals from four different perspectives and scales: soil moisture and vegetation climatology, ground in-situ data comparison, response to precipitation, and vegetation dynamics. Direct comparison of land retrievals with ground in-situ data is, without a doubt, the most important aspect of land algorithm validation. It provides the only means of direct and independent testing of the algorithm theoretical basis and underlying assumptions against ground truth data. It is also important to validate soil moisture data indirectly at global and synoptic scales using climatology and precipitation data. Since soil moisture and vegetation are strongly linked to climate regime and precipitation variability, known statistics and correlations among different land parameters can be used as an indirect test for the land algorithm.
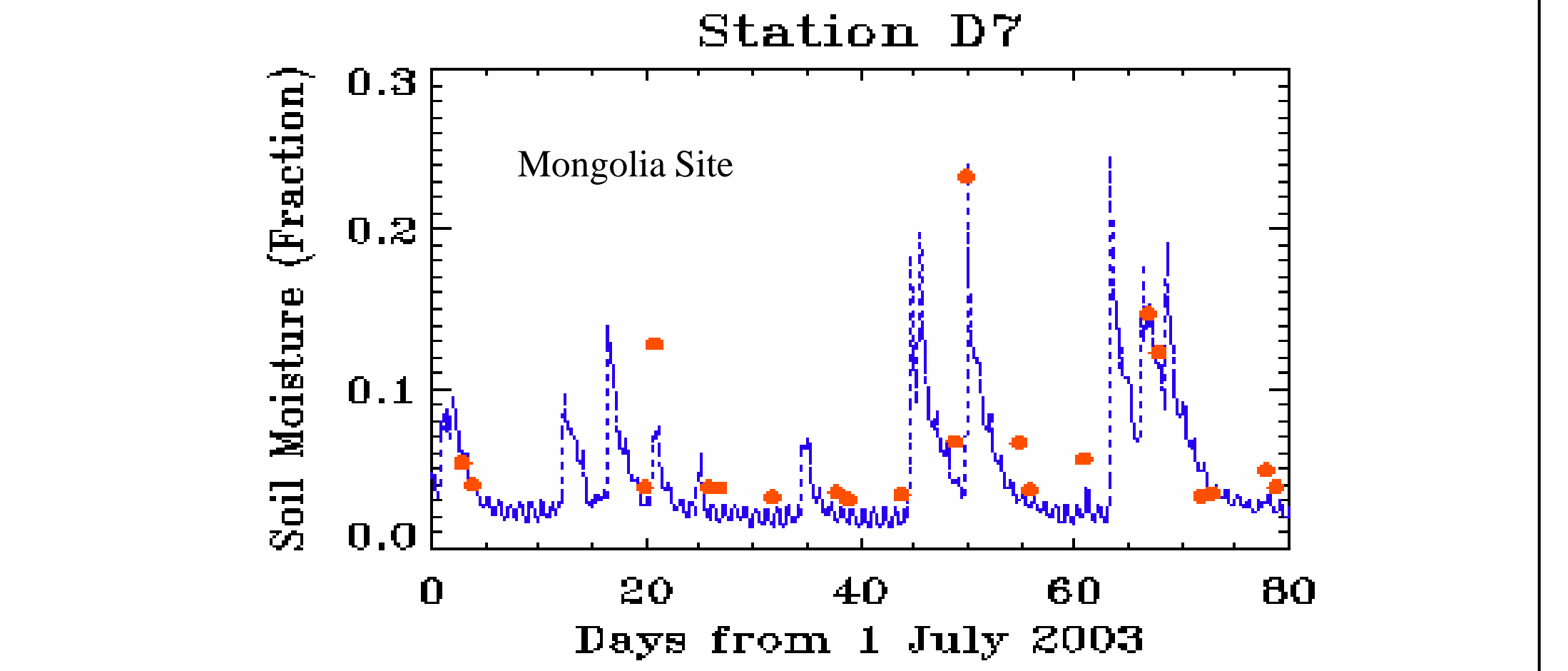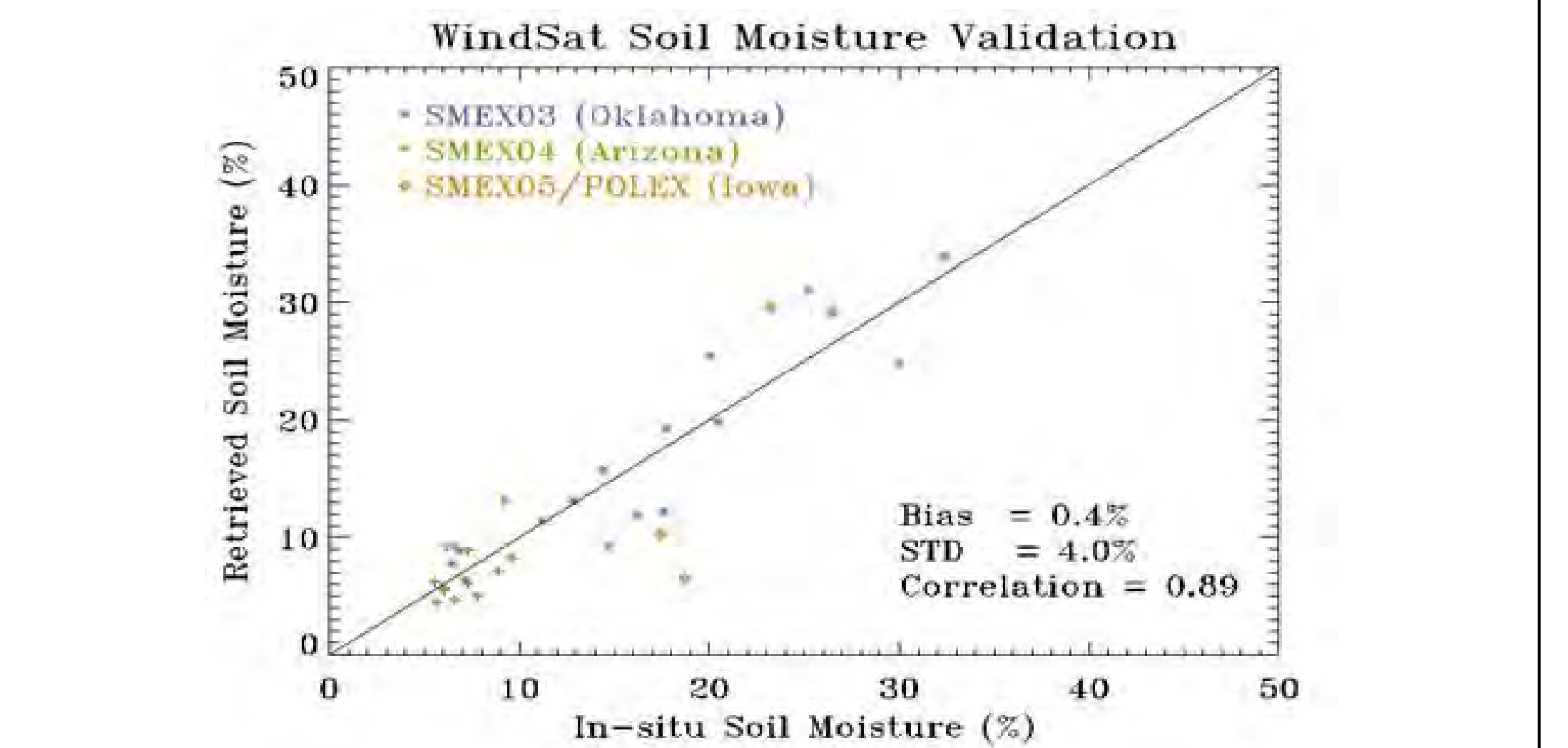
Global Soil Moisture Climatology

- **Climate Regimes:** The soil moisture retrievals are very consistent with global dry/wet patterns of climate regimes. All the deserts and dry regions are well captured by the retrievals. The wet regions in high latitude, stretching from Europe to Asia, are also illustrated well by the high soil moisture retrievals.
- **Correlation with Vegetation:** Soil moisture is roughly correlated with vegetation, which is particularly evident over the dry/wet climate of US. There are some some exceptions in India and Canada. The high soil moisture and low vegetation in Canada is consistent with tundra climatology.
- **Global precipitation climatology:** The high soil moisture distribution shows consistent features with monsoon patterns in Africa, India, China, North America, and Australia.
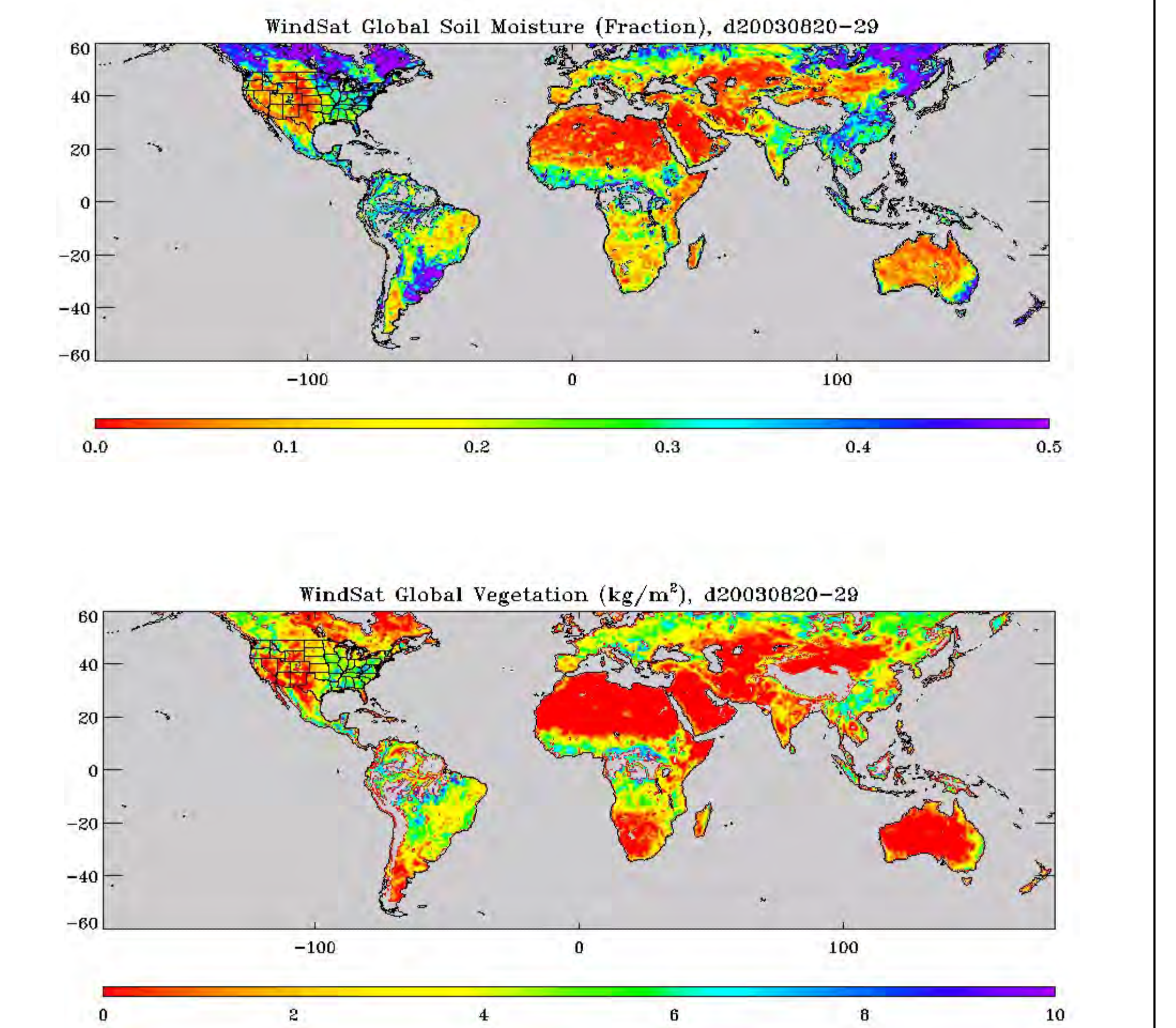
Comparison with ground In-situ

- **SMEX Data Sets:** Densely sampled ground soil moisture data were collected by USDA to validate AMSR-E and WindSat algorithms. The experiment sites include Oklahoma in 2003, Arizona in 2004 and Iowa in 2005.
- **Mongolia Data Set:** Ground Soil moisture data are collected using a sparse network of 16 Automatic Weather Station and Automatic Station for Soil Hydrology. An Intensive Operation Period (IOP) was carried out during summer 2003.
- **Temporal Variations:** Most of the Mongolia stations show temporal variations of soil moisture that are very consistent with WindSat time-series. The correlation coefficients range from 0.77 to 0.96.
- **Error Estimation:** Area averaged soil moisture from SMEX data are compared with WindSat retrievals. An excellent agreement is achieved. The estimated retrieval uncertainty is about 4% with 0.4% bias and 0.89 correlation coefficient.

Conclusions

The WindSat soil moisture algorithm has been developed and validated at the multi-temporal and -spatial scales against soil moisture climatology, ground in-situ network data, precipitation patterns, and vegetation data from AVHRR/MODIS sensors. The results demonstrated the capability of window channel microwave radiometer in meeting soil moisture science requirement under low to moderate vegetation conditions.

Data Release